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PROPERTIES OF FUELS EMPLOYED IN A GAS TURBINE COMBUSTOR PROGRAM

by

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ABSTRACT

A compilation has been made of the physical and chemical properties of sixteen fuels employed in an aircraft gas turbine combustor programme. Several of these are specification fuels of the kerosene or wide-cut type. Others have been chosen to exhibit systematic variations mainly in the direction of out-of-specification boiling range or aromatics level or both. Some are of non-petroleum origin, derived from oil shale or tar sands, or are synthetic fuels (JP10, RJ6). Complete specification testing was conducted on these fuels, and detailed non-specification property determination-simulated distillation by gas chromatography, thermal stability breakpoint, density, specific heat, viscosity, surface tension and true vapour pressure, all as a function of temperature; heats of combustion, hydrogen content, and detailed hydrocarbon compositional analysis.

RÉSUMÉ

La compilation des propriétés physiques et chimiques de seize types de carburant, utilisés au cours d'une étude portant sur les chambres de combustion des turbines à gaz d'aéronefs, vient d'être établie. Parmi ces carburants, plusieurs sont du type kérosène ou à fraction large. D'autres ont été choisis pour mettre en évidence des changements systématiques, principalement ceux qui se manifestent aux limites d'ébullition ou de pourcentage d'aromatique hors-spécifications. Certains sont des carburants synthétiques comme le JP10 et le RJ6, d'atures, dérivés de schistes bitumineux ou de sables asphaltiques, ne sont pas tirés du pétrole. Ces carburants ont été soumis à des essais de spécification complets, à des essais détaillés sur la détermination des propriétés hors-spécification et sur les points suivants: distillation simulée par chromatographie en phase gaseuse; point de rupture de stabilité thermique; densité, chaleur massique, viscosité, tension superficielle et tension de vapeur vraie, tous ces éléments dépendant de la température; chaleur de combustion, teneur en hydrogène et analyse détaillée des composants en hydrocarbures.

INTRODUCTION

Sixteen fuels are being employed in a combustor program conducted by Pratt and Whitney Aircraft of Canada, under the joint sponsorship of the United States Air Force (through the Air Force Wright Aeronautical Laboratories (AFWAL)), the Department of National Defence and the Department of Industry, Trade and Commerce. The work, performed under Contract F33615-80-C-2002, seeks to examine the effect of varying fuel properties on the behaviour of combustors from two engines manufactured by the contractor.

As part of the work, this Establishment arranged for the physical and chemical characterization of fifteen of these fuels. The sixteenth, RJ6, is extremely costly and is to be used only to a limited extent. All property data for this fuel were provided by the USAF, who also supplied the fuel.

This note is a compilation of their properties, with some explanatory material, and assumes a general familiarity with test procedures.

FUELS

No attempt will be made here to give a rationale for the choice of fuels, or more than a few details of preparation or origin. Two specification fuels, a wide-cut, JP4, and a kerosene, Jet A-1, serve as baseline or reference fuels. The properties of the other fuels are varied systematically beyond the specification limited imposed on the reference fuels, principally in the direction of higher final boiling point and higher aromatics content, which corresponds to lower hydrogen content. In addition to this, there are represented certain fuels of unconventional (non-petroleum) origin, and certain fuels not normally consumed in aircraft engines.

1. JP4 - a reference fuel, supplied by the contractor Pratt and Whitney.

2. JP4 B1

3. JP4 B2

These are stocks of (1), JP4, to which two levels of an almost entirely aromatic solvent are added, with the object of reducing the hydrogen content to 13% and 12% respectively. The solvent, 2040, has a boiling range approximately the same as that of typical kerosene gas turbine fuels; it was supplied by AFWAL.

4. Jet A-1 - a reference fuel again supplied by the contractor.

5. Jet A-1 B1

6. Jet A-1 B2

These again are (4) Jet A-1, blended with 2040 solvent, with targeted final hydrogen contents of 13% and 12%.

7. JP4-2040-DF2 - A fuel provided by AFWAL, consisting of JP4 to which 2040 and #2 diesel fuel had been added. The result is a fuel of 13% hydrogen by weight and unusually wide boiling range.

8. Shale Jet A-1 - A fuel prepared from oil shale and refined to meet Jet A-1 specifications.

9. LH

10. HM

11. LM

12. LL

These are four tar sands fuels, prepared by the Research Department of Imperial Oil at Sarnia. The initial L or H signifies a low or high final boiling point; the final L, M or H signifies a (relatively) low, medium and high hydrogen content. As starting materials were employed two products from Suncor's Athabaska operation, a kerocut, somewhat like JP5, with nominal boiling range of 200 - 300°C, and aromatics level about 20%; and secondly a gas oil side stream of nominal boiling range 200 - 350°C, and considerably higher aromatics level, in excess of 40%.

(9), LH is kerocut; (10), HM is a blend of kerocut and gas oil side stream. For the remaining two fuels the gas oil side stream was distilled, and a fraction taken off of the same boiling range as the kerocut. Two blends of the kerocut and this topping were made, to make fuels (11) and (12) of the same boiling range as the kerocut but successively higher aromatics level.

13. No. 2 Diesel was procured locally by the contractor.

14. ERBS (Experimental Referee Broadened Specification) Fuel - provided by AFWAL. A fuel in some ways resembling No. 2 Diesel, with final boiling and aromatics level above specification for aviation fuels.

15. JP10 - hydrogenated dicyclopentadiene, a pure chemical

16. RJ6 - a blend of about 40% JP10 and 60% RJ5, which is a mixture of hydrogenated dimers of norbornadiene.

(15) and (16) are fuels of higher volumetric energy density, employed in cruise missiles and applications in which space is at a premium.

TEST AGENCIES

The information compiled here came from the following sources:

- Quality Engineering Test Establishment, Department of National Defence (QETE)
- Energy Research Laboratory, Department of Energy Mines and Resources (EMR)
- Fuels and Lubricants Laboratory, National Research Council of Canada (NRC)
- Professor J. Odgers, Département de Génie Mécanique, Université de Laval (Laval)
- Mr. R. Tharby, Research and Development Department, Gulf Oil Canada Ltd., Sheridan Park, Ontario (Gulf)
- Prof. J. Desnoyers, Département de Chimie, Université de Sherbrooke (Sherbrooke)
- Dr. D. Steere, Imperial Oil Research Department, Sarnia, Ontario (Imperial)
- Air Force Wright Aeronautical Laboratories
  Wright Patterson Air Force Base
  Dayton, Ohio (AFWAL).

PROCEDURES

Nearly all of these were ASTM test methods, or modifications of them. There was some redundancy or overlap, the same data being provided by

several agencies; and sometimes the same type of information was provided by several agencies; and sometimes the same type of information was provided by two different methods. When partial data were furnished by one source and complete data for the same measurement by another we have generally used for the sake of consistency the complete data only.

When data are obtained by variant or dissimilar methods they are both reported and commented on, in particular if there are disagreements to resolve.

TABLE I D86 Distillation (QETE)

TABLE II D2887 Simulated Distillation by g.c. (EMR)

These distillations were carried out in two lots, fuels 1, 2, 5-8, 13-15 being examined some months before 3, 4 and 9-12. This accounts for the difference in presentation (in degrees and tenths of a degree), and must also be responsible for the discrepancy between JP4 B1 and JP4 B2; one would expect the boiling point at any level of recovery to be higher, not lower, for JP4 B2.

TABLE III Thermal Stability (QETE)

Fuels were examined in the Jet Fuel Thermal Oxidation Tester (JFTOT) in two ways. First, a pass or fail test was conducted according to D3241 at the generally adopted temperature of 260°C. Fuels were recorded (row 1) as pass (P) or fail (F), by one of two criteria, a pressure build-up (row 2) of greater than 25 mm during the 2½ hour course of the test; or (row 3) a visual rating of 3 assuming the normal (N) sequence of color development is observed (row 4). It is generally accepted that certain abnormal (A) color developments or observation of a series of interference colors - peacock (P) are cause for failure regardless of the color rating. Several abnormal and peacock observations are listed in row 4. It is seen that all fuels that did fail, except for No. 2 Diesel, failed by pressure build-up.

In addition, some tubes were examined in the tubing deposit rater, which gives an alternative and supposedly more objective measurement of color density by reflectance. Averaged observations along the length of the tube while it was rotated (spun) and determination of the individual point of maximum light absorption (spot) are recorded.

TDR readings for the two failures among the fuels so examined (JP4 B1 and No. 2 Diesel) are quite large, exceeding the TDR spot reading of 15 which has been proposed as a criterion of failure.

The concept of breakpoint was introduced a few years ago in an attempt to quantify fuel thermal stability by defining a temperature at which some observation made with JFTOT exceeds a critical value. The fuel is run in the JFTOT at several temperatures, and by interpolation of results the lowest temperature is found at which either pressure build-up exceeds

25 mm or the color rating (assuming the normal sequence of color development) reaches 3.

Breakpoints and failure modes are listed in the lower half of Table III. The determination is not precise, and an uncertainty of at least ±5°C is to be expected. In principle a fuel with a breakpoint below 260°C should fail the specification test. As can be seen, JP4 which originally passed the specification test gave a breakpoint on visual at 239°C. In addition JP4 B2, which failed the specification test on pressure was limited in breakpoint determination by color development. However the JP4 had been observed to contain sediments and to require extensive filtering before thermal stability testing, and results with it and its 2040 blends were variable and not satisfactory. Contamination of the original stock of JP4 appears very probable.

TABLE IV.

Densities at 15°C were determined at QETE, using D1298, and at four temperatures at Sherbrooke. Here, a Picker dynamic densimeter was used to determine density at the reference temperatures of 25°C. Thermal expansion coefficients were then measured for each fuel with high precision, and by an integration process densities at other temperatures could be calculated. QETE results fell quite satisfactorily on the curve obtained by plotting the Sherbrooke data.

The densities listed for RJ6 were calculated from data provided by AFWAL, a density measurement at 15°C, and a curve relating density to temperature presumably of general validity for fuels of this type.

Specific heats as a function of temperature were determined at Sherbrooke, employing the Picker differential dynamic microcalorimeter.

Viscosities for fifteen fuels were determined at QETE, by D445, and for RJ6 were calculated from data supplied by AFWAL. The viscosity of RJ6 at -65°F (-54°C) was 423.90 cSt, higher than the specification limit of 400 cSt at that temperature.

Surface tension (Laval) was determined by a capillary rise technique, employing benzene as a reference fluid.

TABLE V. Vapor pressure (Laval). The method employed is a modification of the isoteniscopic procedure of D2879-75. For a mixture of many components such as a liquid fuel, the vapor pressure is not defined uniquely by temperature, by depends on the ratio of vapor to liquid volume. As this ratio approaches zero the contribution of the volatile components becomes increasingly important, and the vapor pressure approaches a limiting value. In the present work four isoteniscopes of V_v/V_L varying from 0.06 to 0.280 were used. These ratios are considerably smaller than those used in most previous work, and the results in consequence reflect more closely the limiting intrinsic value. Considerable manipulation of the experimental data is necessary in order to make correction for the air inevitably retained by the fuels. The original report should be consulted for details

of this data treatment. What is presented in Table V is a very small portion of the data generated, and is intended only to be representative of the information available in the report. Table V contains the experimental data at the two higher Vv/V_L ratios, 0.280 and 0.184, and the derived or corrected data at the highest Vv/V_L ratio (.280) and the limiting value $Vv/V_L = 0$. (The experimental data marked with an asterisk are derived by a short extrapolation from the experimental points in the original report.)

The original report comments on the extreme difficulty in getting error-free results, and the fact that anomalies can occur even if meticulous care is exercised. An instance of this is found on comparing data for JP4 B1 and JP4 B2.

The latter fuel contains more 2040 solvent, and in view of the boiling ranges of JP4 and 2040 solvent, it should have under the same conditions a lower vapor pressure than JP4 B1, not higher, as observed. This anomaly occurs both in the experimental and the derived data. Again, the experimental vapor pressure data for fuel LM appears abnormally high at $Vv/V_L = 0.280$. This is probably due to trapped air, as the irregularity has disappeared in the corresponding derived data, presumably being removed by the correction procedure referred to above. JP10 is supposedly a pure compound, and one would expect to find its vapor pressure at any temperature independent of liquid-vapor ratio. Instead some dependence similar to that of the other fuels is observed. This can be attributed either to residual air or to the presence of small amounts of light material not removed during production. The D2887 distillation of JP10 (Table II) suggests that both light and heavy ends may be present.

Table VI Flash Points D56 - 11 fuels - QETE

D 3828 (Setaflash) - 15 fuels - Laval

There is significant disagreement in the case of the less volatile fuels.

Freeze points D2386 (QETE)

Setapoint (NRC)

D2386 records the disappearance of the last wax on rewarming; it has been reported that the Setapoint reflects rather the wax appearance point, so that Setapoint measurements tend to be systematically lower than D2386. This observation is in general supported by examination of the data (omitting JP10 as anomalous). For fuels containing middle distillate fractions (JP4-2040-DF2, tar sands fuels, No. 2 diesel, and ERBS) Setapoint measurements are from 2 to 6° lower than D2386. For the lighter JP4 and Jet A1 - based fuels, the two measurements coincide within a degree, with the single exception of JP4 B1, in which the Setapoint reading is 2° higher.

Smoke point (D1322) data were provided by QETE and Gulf; Gulf also provided luminometer data (D1840).

Heats of combustion (D2382) were provided by EMR, and for comparison, calculated heats of combustion (D1405) from aniline-gravity product (QETE).

This latter determination is included as a matter of interest, as the aniline-gravity estimation applies only to petroleum-based fuels that meet a recognized specification (aviation gasoline, JP4, Jet A, etc.). Taking the D2382 heat of combustion figures as correct, and examining the D1405 figures, significant disagreement is seen with JP4 and its blends, and with Jet A1 B2. Calculated heating values for tar sands fuels are surprisingly good.

Table VII. The first two rows compare hydrogen content as determined by NMR (D3701) at NRC, and by microcombustion (EMR). The latter figures are typical of the best that can be achieved by classical methods.

It is seen that attempts to reach 13 and 12% hydrogen by addition of 2040 solvent to the two base fuels were not completely successful. The test laboratory (NRC in Ottawa) was not easily accessible to the blending site and it was difficult to adjust blend ratios and test reiteratively.

Hydrogen content of JP10 was calculated from its formula; and for R16 from its composition (39.9% JP10, 59.9% RJ5) supplied by AFWAL.

D1319. Fluorescent indicator adsorption (QETE). This analysis provides a rough division into three fractions - aromatics, olefins and paraffins. Developed for gasoline and turbine fuel of petroleum origin it provides an estimate of proportions, and results depend to some extent on operator techniques; only with considerable reservations can it be used for other fuels. The D1319 data provided by Imperial for the four tar sands fuels are included with the QETE values, and show the kind of variation that can be expected.

D1840 Naphthalenes (QETE). This estimation is made by light absorption in the near ultra violet. For the JP4 and Jet A-1 blends, with 2040 solvent, the naphthalene content can be calculated from the blend ratio, and the knowledge that 2040 solvent contains 57% naphthalenes. Results from D1840 come out in quite satisfactory agreement with these calculated values even though D1840 is a rather rough method of estimation.

Detailed hydrocarbon compositional analysis was carried out by EMR, employing a modification of D2789. The original results were presented as paraffin; naphthenes in two categories; and aromatics broken into six categories. In this summary they have for purposes of comparison been reconsolidated into paraffins, naphthenes and aromatics. The analytical program is so devised that olefins, low in any case, always appear as zero. Paraffins, naphthenes and aromatics add up to 100% apart from rounding off errors. Again, naphthalenes are shown as a separate category.

Comparing the two sets of data from the two sources, it appears that in particular for high aromatics fuels D2789 understates the aromatics level. In the case of one blend, Jet A1 B2, figures for both aromatic and naphthalene content are significantly lower than what may be called "true" values, calculated from the blend ratio and the composition of Jet A1 and 2040. Much the same observation may be made about the four tar sands derived fuels. From the available data on the kerocut and gas oil side stream rough compositions for the blends can be worked out. Either of the two D1319 analyses, for all their uncertainty, is closer to this "true"

value than the D2789 results. It is evident that with this latter method at high aromatic levels a saturation effect has led to a compression in the aromatic readings.

Data by either of the two methods may be taken as indicative of trends in composition and used for comparative; however the D1319 data are closer to the actual composition.

The last three determinations, total sulfur (D1266), mercaptan sulfur (D1323) and nitrogen (D3228) were performed at QETE. The sulfur determinations are all within specification for aviation turbine fuels. Nitrogen levels, for which no specification exists, are in the range anticipated.

ACKNOWLEDGEMENTS AND DATA SOURCES

The compilers are greatly indebted to the eight agencies listed on page 4, whose efforts provided all the data recorded here. Responsibility for selection among the very extensive data in several of the reports is the compilers'.

Some of the information was received as letters or informal verbal communications; the following formal reports, containing the bulk of the information, are available through the DREO Library:

- NRC LTR-FL-206, April 22, 1981

- NRC LTR-FL-220, March 1, 1982
  (hydrogen content by NMR, freeze point by Seta apparatus, surface tension at 77°F (25°C)).

- Université Laval, Département de Génie Mécanique, Report No. j.o. 104, April 1982, DSS Contract No. 09SU.97714-0-1017.
  (flash point, vapor pressure, surface tension).

- Université de Sherbrooke, Département de Chimie, February 1982. DSS Contract No. 20SU.97714-0-1016
  (specific heats).

- Quality Engineering Test Establishment, Department of National Defence.
  Project A01439 February 1981
  Project A03171 February 1982
  Annex to
  Project A03171 May 1982
  (complete specification testing, JFTOT breakpoints).

TABLE I

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	JP4	JP4 B1	JP4 B2	JP4 2040 DF2	JET A1	JET A1 B1	JET A1 B2	JET A1 SHALE	KEROCUT LH	KC+GOSS HM	KC+GOSS TOPPING LM	KC+GOSS TOPPING LL	DIESEL #2	ERBS	JP10	RJ6
D86 I.B.P. °C	61	64	58	68.5	169	173	174	175	171	172	174	182	191	187	178	
5	88	92	91	99	177	180	183	184	197	192	194	197	223	197	181.5	
10	99	104	108	114	181	184	185.5	186	203	200	200	204	233	200	182	
20	117	126	131	141.5	186.5	191	192	189	211	214	210	213	246	208	182.5	
30	132.5	143	155	161	189.5	194	195	191	217	221	215	219	255	215	183	
40	147	160	173	194	193	197	200	195	223	227	223	225	263	220	183	
50	159	175	185	213	196	201	204	199	229	233	229	232	271	226.5	183	
60	169.5	186	197	230	200	206	210	204	234	240	236	238	280	235	183	
70	178	197	210	247	205	211	217	209	241	249	242	245	290	241	183	
80	187	209	223	265	210	218	224.5	217	249	259	249	254	301	260	183.5	
90	199.5	229	243	292	219	232	238	226	260	275	261	265	316	288	184	
95	210	248	258	319	229	245	253	235	270	296	271	278	334	309	184	
96	214	253	263	328	234	251	257	238	274	304	275	283	338	315	185	
E.P	218.5	263	268	329.5	244	266.5	272	248	283	311	288	285	346	329	195.5	
RECOVERY %	97.5	98	97.6	97.0	97.5	98	98.5	98.5	98.0	97.7	98.3	97.3	98.0	98.5	98.5	
RESIDUE	1.4	1.1	1.4	1.6	1.4	1.2	1.2	1.5	1.8	1.9	1.5	2.4	1.7	1.5	1.0	
LOSS	1.1	0.9	1.0	1.4	1.1	0.8	0.3	-	0.2	0.4	0.2	0.3	0.3	-	0.5	

TABLE II

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	JP4	JP4 B1	JP4 B2	JP4 2040 DF2	JET A1	JET A1 B1	JET A1 B2	JET A1 SHALE	KEROCUT LH	KC+GOSS HH	KC+GOSS TOPPING LM	KC+GOSS TOPPING LL	DIESEL #2	ERBS	JP10	RJ6
D2887 0.5%	30	44	29.9	33.0	131	133	135	146	131.5	128.8	123.7	132.9	148	145	169	
5	64	85	67.8	72.4	157	159	161	162	167.5	171.0	169.0	171.8	201	170	170	
10	82	111	94.9	96.7	165	167	170	169	185.4	189.7	186.8	187.8	218	182	172	
20	105	143	132.0	133.4	175	178	183	177	202.5	205.8	203.8	204.2	239	197	176	
30	127	169	159.5	168.7	184	188	193	186	212.1	215.3	213.0	213.9	255	208	179	
40	145	191	175.8	197.0	193	195	200	194	220.3	225.7	222.8	224.2	270	216	181	
50	159	204	192.6	214.3	197	201	206	200	229.6	235.4	232.1	233.5	281	226	182	
60	169	217	204.1	230.9	203	207	212	208	238.8	245.9	241.2	243.2	293	237	184	
70	180	231	218.1	250.1	206	213	220	213	249.0	256.7	251.0	252.9	308	248	186	
80	194	249	229.8	272.1	214	221	227	223	259.7	270.4	262.0	264.3	322	270	187	
90	205	267	245.8	301.6	225	234	243	235	273.5	286.1	275.6	278.3	339	300	189	
95	213	280	256.9	326.2	235	246	256	246	283.3	305.2	285.8	289.6	353	326	190	
99.5	235	326	295.8	372.0	280	292	299	284	-	360.7	329.1	331.8	401	428	323	

Note: Fuels 3, 4, 9-12 were run at one time,
the balance at another time, by the same agency.

TABLE III

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	JP4	JP4 B1	JP4 B2	JP4 2040 DF2	JET A1	JET A1 B1	JET A1 B2	JET A1 SHALE	KEROCUT LH	KC+GOSS HH	KC+GOSS TOPPING LH	KC+GOSS TOPPING LL	DIESEL #2	ERBS	JP10	RJ6
JFTOT D3241 At 260°	P	F	F	F	P	P	P	P	F	F	F	F	F	P	P	
P mm Hg	2.5	254	254	254	3	7.5	1.0	0.5	38	254	254	254	2.5	2	2	
VISUAL	1 N	3-4 A	4 P	3-4 N	1 N	1 N	1 N	1 N	1 N	1 N	1 N	4 A	1 A	1 N	1 N	
Δ TDR (a) SPUN	3	43.5	-	-	0	0	0	0	-	-	-	-	13.5	5	0	
(b) SPOT	4.5	45	-	-	2	0	1	1	-	-	-	-	17.5	7	0	
BREAKPOINT °C	238	212	203	247	277	274	274	276	246	229	250	258	258	292	313	
P mm Hg	0	25	1	25	25	6	5	25	25	25	25	25	2	1	-	
VISUAL	3	1	3	2	1	3	3	1	1	1	1	1-2	3	3	-	

TABLE IV

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	JP4	JP4 B1	JP4 B2	JP4 2040 DF2	JET A1	JET A1 B1	JET A1 B2	JET A1 SHALE	KEROCUT LH	KC+GOSS HM	KC+GOSS TOPPING LM	KC+GOSS TOPPING LL	DIESEL #2	ERBS	JP10	RJ6
DENSITY Kg/L																
5°C	.77480	.81543	.84472	.82897	.81201	.83580	.85913	.81013	.84457	.85055	.84920	.85480	.85762	.84792	.94620	1.0245
D1298 15	.7668	.8078	.8359	.8215	.8048	.8289	.8518	.8033	.8380	.8436	.8434	.8481	.8509	.8417	.9377	1.0185
25	.75964	.80032	.82970	.81443	.79788	.82161	.84484	.79603	.83086	.83650	.83542	.84093	.84432	.83427	.93139	1.0100
45	.74447	.78520	.81362	.79987	.78372	.80740	.83053	.78192	.81714	.82244	.82163	.82074	.83100	.82061	.91657	.9955
65	.72930	.77008	.79767	.78532	.76957	.79318	.81623	.76781	.80342	.80838	.80784	.81315	.81769	.80696	.90175	.9815
SPECIFIC HEAT J/Kg DIFFERENTIAL MICROCALORIMETRY																
5°C	1.9310	1.8498	-	1.8508	1.8913	1.8429	1.7983	1.9143	1.8246	1.8164	1.8168	1.8084	1.8488	1.8496	1.5185	-
25	2.0026	1.9186	-	1.9180	1.9680	1.9142	1.8625	1.9838	1.8992	1.8896	1.8906	1.8469	1.9193	1.9152	1.5999	-
45	2.0896	1.9963	1.9366	1.9991	2.0489	1.9873	1.9377	2.0650	1.9945	1.9724	1.9744	1.7630	1.9973	1.9922	1.6868	-
65	2.1816	2.0831	2.0212	2.0894	2.1465	2.0824	2.0208	2.1561	2.0985	2.0872	2.0832	2.0713	2.0883	2.0804	1.7965	-
VISCOSITY cSt																
D445 -20°C	1.85	2.15	2.52	3.46[1]	3.93	4.07	4.36	4.17	8.10	9.20	8.01	8.55	-	8.16	8.84	41.3
0°C (32°F)	1.29	1.45	1.66	2.35	2.39	2.46	2.56	2.52	4.15	4.55	4.06	4.31	8.63	4.19	5.08	15.9
21.1°C (70°F)	1.00	1.07	1.18	1.60	1.65	1.62	1.70	1.70	2.55	2.77	2.53	2.67	4.53	2.55	3.26	9.15
37.8°C (100°F)	0.790	.877	.955	1.26	1.28	1.27	1.30	1.35	1.85	1.96	1.82	1.88	3.03	1.85	2.37	7.05[2]
SURFACE TENSION (dyne/cm)																
CAPILLARY 0°C	24.7	26.9	26.0	24.4	27.95	28.2	29.2	26.95	28.5	29.1	28.8	28.5	29.5	30.2	-	
25	22.5	24.1	23.9	23.4	25.35	26.2	26.95	25.1	26.4	26.8	26.6	26.2	26.3	27.2	32.1	
50	20.35	21.4	22.0	21.4	22.9	24.3	24.8	23.1	24.3	24.7	24.6	24.2	25.3	24.4	29.8	
75	18.2	18.7	20.0	19.5	20.3	22.3	22.45	21.5	22.1	22.5	22.5	21.9	23.2	21.5	27.4	

Note 1. By extrapolation. A value of 5.438 cSt reported by AFWAL contractor at -28.9°C, is consistent with this data, although the fluid was hazy, indicating some phase separation.

Note 2. By extrapolation.

TABLE V

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
		JP4	JP4 B1	JP4 B2	JP4 2040 DF2	JET A1	JET A1 B1	JET A1 B2	JET A1 SHALE	KEROCUT LH	KC+GOSS HM	KC+GOSS TOPPING LM	KC+GOSS TOPPING LL	DIESEL #2	ERBS	JP10	RJ6
Vapour Pressure (mm Hg) D2879-75 Modified																	
Experimental Data	0°C	52*	39*	54*	30.5*	25.5*	33.5*	49*	30*	23*	17*	45.5*	22*	20.5*	35.5*	32*	
Vv/Vl = 0.280	25	112	87	111	80	42.5	53	63	56	46	28	67	40	35.5	57	43	
	50	220	172	211	173	62	77	87	88	83	42.5	92	77	52	84	62	
	75	395	325	368	310	90	110	131	140	120	65	140	105	74	115	100	
Vv/Vl = 0.184	0	73*	61*	77*	48*	33*	48*	67*	42.5*	78*	62*	61*	97*	37*	58*	42*	
	25	158	120	151	121	66	68	85	73	130	91	90	145	61	120	61	
	50	292	222	290	275	103	85	124	118	202	130	134	200	95	215	87	
	75	510	410	530	480	150	118	180	180	253	160	195	250	139	350	132	
Derived Data	0	34	29	45	26.5	12	22	7	23.5	23	10	10	15	-	23	-	
Vv/Vl = 0.280	25	85	70	95	67.5	24	48	18	43.5	43	17.5	21	30.5	14	38.5	12	
	50	187	153	184	152	43	61	39	76	75	32.5	48	57.5	30	61	29	
	75	365	300	325	305	68	92	75	122	120	58	97	99	57	90	61	
Vv/Vl = 0.0	0	74	94	158	70	73	164	60	78	217	44	87	198	93	207	25	
	25	173	190	360	188	157	290	137	149	400	92	205	355	208	380	66	
	50	380	370	770	445	310	478	290	268	675	175	435	610	425	650	155	
	75	740	650	-	930	545	725	540	440	~1050	305	825	940	780	1000	320	

* Derived by short extrapolation from experimental points.

TABLE VI

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	JP4	JP4 B1	JP4 B2	JP4 2040 DF2	JET A1	JET A1 B1	JET A1 B2	JET A1 SHALE	KEROCUT LH	KC+GOSS HH	KC+GOSS TOPPING LH	KC+GOSS TOPPING LL	DIESEL #2	ERBS	JP10	RJ6
FLASH POINT																
D56-TAG °C	-	-	-	-	53.5	55.0	57.0	54.5	63.0	63.5	62.0	64.0	68.0	66.0	50.5	65.5
D 3828-SETAFLASH °C	-18	-14	-13.5	-7.5	55.5	56.0	59.0	55.5	66.0	67.0	64.5	67.5	73.0	69.0	52.5	
FREEZE POINT																
D 2386 °C	-73	-61	-47.5	-25	-60	-63	-53	-52	-48.5	-49	-48	-49	-13	-24	-73	
SETAPOINT °C	-70	-59	-47.5	-31	-59.5	-62	-54	-51	-50.5	-52.5	-53.5	-53.5	-15.5	-26.5	-70	
SMOKE POINT mm D 1322	28.5	14.9	10.0	14.5	22.8	15.9	11.5	24.2	16.0	17.0	16.0	15.0	15.7	15.5	16.6	
SMOKE POINT D 1322	27	14	12	14	22	17	12	22	17	16	16	14	15	14	17	
LUMINOMETER NO D 1740	63	34	19	31	46	29	21	51	35	31	32	28	29	28	30	
HEAT OF COMBUSTION MJ/kg D 2382	43.82	43.16	41.90	42.80	43.04	42.99	43.52	43.30	42.87	42.66	42.80	42.80	43.21	43.07	42.81	41.99
ANILINE POINT °C D 611	52.5	35.8	22.4	46.1	56.1	44.4	31.8	56.9	55.4	52.8	50.0	45.9	62.5	53.3	(27)	
NET HEAT OF COMBUSTION (CALC) D 1405 MJ/kg	43.46	42.85	42.47	42.94	43.17	42.80	42.47	43.20	42.93	42.84	42.80	42.70	-	-	-	

TABLE VII

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	JP4	JP4 B1	JP4 B2	JP4 2040 DF2	JET A1	JET A1 B1	JET A1 B2	JET A1 SHALE	KEROCUT LH	KC+GOSS HH	KC+GOSS TOPPING LH	KC+GOSS TOPPING LL	DIESEL #2	ERBS	JP10	RJ6
HYDROGEN WT % D3701	14.25	12.86	11.93	13.01	13.76	12.88	12.04	13.82	13.38	13.21	13.17	13.03	13.05	12.96	11.88[1]	10.55[1]
MICROCOMBUSTION	14.2	12.9	12.09	12.89	13.9	13.0	12.4	14.0	13.21	13.09	13.03	12.83	12.9	13.2	12.0	-
D1319 COMPOSITION[2]	84.6	69.1	56.7	70.8	78.9	68.5	57.4	77.0	69.1 (78)	65.4 (70)	61.0 (66)	56.4 (63)	64.9	69.6	98.5	-
PARAFFINS % V	14.5	30.2	42.5	28.3	19.7	30.2	41.7	21.1	29.1 (20)	33.4 (28)	37.2 (32)	41.8 (36)	31.9	29.1	0	-
AROMATICS	0.9	0.7	0.8	0.9	1.4	1.3	0.9	1.9	1.8 (2)	1.2 (2)	1.8 (2)	1.8 (1)	3.2	1.3	1.5	-
OLEFINS																
D1840 NAPHTHALENES %V	0.3	11.0	17.6	10.7	0.7	9.2	17.3	0.6	1.0	1.7	1.3	1.6	7.8	12.5	0	-
D2789 MODIFIED																
PARAFFINS %V	49.3	43.8	41.9	47.6	48.7	43.8	43.0	51.6	39.2	38.1	38.0	36.6	43.6	43.6	-	-
NAPHTHENES	35.9	30.0	25.1	29.0	35.1	30.7	28.4	30.8	41.3	40.7	40.0	38.7	28.4	27.2	-	-
AROMATICS	14.8	26.3	33.0	23.4	16.2	25.5	28.6	17.6	19.6	21.3	22.0	24.2	28.0	29.2	-	-
NAPHTHALENES (FROM AROMATIC FRACTION IN D 2789)	1.1	10.1	16.2	8.9	1.3	9.0	11.7	1.2	1.0	1.3	1.4	1.5	4.9	7.5	-	-
D1266 TOTAL SULFUR % W/W	0.044	0.036	0.0034	0.085	0.004	0.005	0.003	0.003	0.003	0.024	0.019	0.024	0.241	0.050	0.002	
D484 MERCAPTAN S% W/W	0.0012	0.00089	NEG	NEG	0.00058	0.00038	0.00035	0.00042	NEG	NEG	NEG	NEG	0.00086	0.00082	0.00058	
D3228 NITROGEN % W/W	0.0001	0.0001	0.0015	0.003	0.0020	0.0019	0.0019	0.0164	.0013	.007	0.018	0.021	0.0109	0.0000	0.0000	

1. Calculated
2. Bracketed data for the four tar sands fuels were supplied by Imperial Oil, who prepared the fuels.

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13 ABSTRACT

A compilation has been made of the physical and chemical properties of sixteen fuels employed in an aircraft gas turbine combustor programme. Several of these are specification fuels of the kerosene or wide-cut type. Others have been chosen to exhibit systematic variation mainly in the direction of out-of-specification boiling range or aromatics level or both. Some are of non-petroleum origin, derived from oil shale or tar sands, or are synthetic fuels (JP10, RJ6). Complete specification testing was conducted on these fuels, and detailed non-specification property determination-simulated distillation by gas chromatography; thermal stability breakpoint; density, specific heat, viscosity, surface tension and true vapor pressure, all as a function of temperature; heats of combustion, hydrogen content, and detailed hydrocarbon compositional analysis.

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